SECTION I

GENERAL

Introduction

It will be recollected that in our letter of 8th July, 1965 we submitted proposals including a Programme and Estimate of Costs for a full feasibility study estimated at £324,000 and occupying a period from August 1965 to February 1969. Subsequently, as a result of a policy decision to cut down on capital expenditure for a while, on 21st October we submitted proposals for a "Desk Study" in which we suggested that for a comparatively modest expenditure it would be possible to arrive at a preliminary view on the viability or otherwise of this project. Our estimate for the "Desk Study" amounted to £15,000 which included £5,000 for the purchase of an existing survey carried out by Messrs. Hunting on behalf of Messrs. C.S. Allott & Partners. The latter had been associated with the late Mr. Leeming who had long advocated the construction of a barrage across Morecambe Bay and had made certain proposals.

Terms of Reference

2. New Terms of Reference were accordingly agreed, reference your letter of 9th November, 1965, and these are set out below. Our Report is drawn up to follow these Terms as closely as possible.

(1) The quantity of water which can be made available:

(a) the amount and variability of run-off.

(b) the storage which can be provided.

(c) the yield/storage relationship.

(d) the net yield to supply.

(2) The problems associated with making the water potable:

(a) the quality of the water draining from the catchment.

(b) residual contamination in the Bay.

(c) contamination from the sea.

(d) final quality of stored water and required treatment.

(3) The probable cost of making that quantity of water available:

(a) the barrage structure - location, dimensions, materials and costs.

(b) the methods and costs of closure.

THE QUANTITY OF WATER WHICH CAN BE MADE AVAILABLE

Catchment Area

The catchment area, which amounts to some 300,000 acres (1200 km^2), is shown on Figure 1 with the isohyets and the principal rivers. It is roughly rectangular in shape, lying for the most part in the county of Westmorland. It extends from the Langdale Pikes in the north-west to Whinfell Beacon in the east. Some 12% of the catchment is more than 1000 ft. (304.88 m) above sea level and 2% is more than 2000 ft. (609.76 m) above sea level. The area is diversified with woodlands, pasture, a good deal of rough fell and very little arable. The geology of the area, which is for the most part impermeable, is discussed in Appendix B.

Rainfall

2. The range of altitude over the catchment is considerable and precipitation differs appreciably, some 20% of the area to the north-west having an annual rainfall of about 100 inches (2564 mm), while the average over the whole area, based on records over 33 years, is 66 inches (1692 mm).

Run-off

3. The quantity of water that can be made available is dependent on two main factors; first, the quantity and variability of the run-off discharging into Morecambe Bay from the catchment, and, second, the volume of storage that can be provided in the reservoir above lowest draw down level. Each of these considerations is further dependent on a number of complex factors, and while the assessment of the discharge into the reservoir consists of estimating the effect of existing conditions, man-made works having no material effect on the situation, the volume of effective storage that can be provided in the reservoir is essentially a matter of engineering practicability and economics and is dealt with later in the report. This section discusses the estimation of the quantity of water that would discharge into the reservoir on the basis of information available at present.

4. The most desirable data for this purpose is a continuous and reliable record of measured discharges in the rivers concerned over a period of many years. Information is available for the Leven and Crake Basins for the periods 1940 to 1943 and 1946 to the present time. However, except for the period 1963/65 referred to below, the data exists only in the form of weekly recorder charts and it has not been practicable to examine and analyse this data in the time available. Photo copies of the weekly charts for the short period from 28th December, 1960 to 1st May, 1961 have been studied to ascertain the

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	6		9	15	20	20	15	9		6	

The above figures are necessarily approximate and in the view of the Meteorological Office they are applicable to land areas and small water areas in the British Isles. For larger water areas there may well be a tendency for a greater proportion of the evaporation to take place in winter but much will depend on environment. A special study of evaporation off the surface of the reservoir is clearly required.

It has been assumed that the loss in a given month would not exceed the total rainfall in that month; losses in the period October to March have been taken as uniformly distributed. The estimated monthly run-off over the 33 years from 1932 to 1964 has been plotted on a cumulative discharge diagram. See Fig. 7.

The following points are of interest. First, the drought period 1933-1935 that obtained over many parts of the country did not produce the three driest consecutive years for this catchment, where the rainfall after August in 1935 was considerable. The three driest consecutive years were in fact from the 1st August 1939 to 31st July 1942. Second, the estimated run-off over the three driest consecutive years is fairly uniform so that it may well be that this three year period will not be the most critical when considering the relationship between yield and storage. This point is considered later. See paragraph 14 below.

Volume of storage in reservoir

8. The effective volume depends on the following :-

(a) the alignment of the barrage

(b) normal retention level and lowest draw down level

(c) possible treatment of the shores of the reservoir.

The height of the barrage has been determined by the need to exclude salt water rather than to retain fresh. Its design and construction are discussed in Section IV. In considering its location, in the first instance, an alignment known as "the Leeming line" was studied. This was principally for reasons of convenience in that there were available volumetric tables co-relating levels and capacity. It became apparent, however, that with the Leeming line the possibility of obtaining a yield of say 500 m.g.d. (26.30 m^3/s) would be doubtful within a practicable range of reservoir levels. It was for this reason that a new alignment has been adopted for this Report.

9. To fix normal retention level, apart from amenity considerations and the presence of roads and buildings, the level must be determined in relation to the constant tail water level at which rivers can discharge into the reservoir and the afflux levels in critical sections of the

general characteristics of the normal river hydrograph at the gauging point at Newby Bridge. Other data studied include a stage duration summary from the above data, covering 8035 days, and tabulated monthly river discharges from May 1963 to September 1965 for the Leven at Newby Bridge, and from October 1963 to September 1965 for a gauge on the Crake at Low Nibthwaite, near the outfall from Coniston Water. For the purpose of this study it has, therefore, been necessary to estimate the magnitude and variability of river discharge from rainfall data, and run-off has been calculated from the rainfall records provided by the Meteorological Office from 1932 to 1964 with an allowance made for losses as described below.

5. The estimated run-off has been compared with a record of flow in the river Leven over the period 1963 to 1965 and on this basis it appears that the estimate may be conservative. However, the period over which the comparison has been made is too short to be taken as anything more than an indication of probabilities.

6. Rainfall data has been made available by the Meteorological Office in two forms :-

(a) tabulated monthly rainfall from 1910 to 1965 for 5 primary and one secondary rain gauges

(b) a plot of the isohyetal lines for the standard period 1916 to 1950.

On examining the data referred to in (a) above it was noted that one of the rain gauges (Fisher Tarn) was "over exposed" prior to 1932, giving readings that were too low. As this gauge represents an appreciable portion of the catchment, it was considered preferable to disregard the figures before 1932 in estimating the total monthly run-off. The monthly run-off has, therefore, been estimated for the years 1932 to 1964, a period of 33 years. Estimates of run-off were made in accordance with Thiessen's method, the catchment being divided into six sub-divisions. The average annual rainfall for each of these sub-divisions was first compared with a figure obtained by measuring the areas between the isohyets. From this comparison a rain gauge factor was obtained for each of the six areas and this factor has been used in computing monthly rainfall figures. The estimated average achieved by this means for the whole catchment is 66 inches (1692 mm).

7. The Meteorological Office have suggested average losses of 18 inches (461.52 mm) per annum over the land area and 21 inches (538.44 mm) over the reservoir. These figures may well prove to be somewhat high but we have adopted them for the time being, pending further investigation.

In considering estimated monthly run-off it is necessary to apportion annual losses over the 12 months of the year. Following discussions with the Meteorological Office we have apportioned these losses as percentages as follows :-

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	6		9	15	20	20	15	9		6	

The above figures are necessarily approximate and in the view of the Meteorological Office they are applicable to land areas and small water areas in the British Isles. For larger water areas there may well be a tendency for a greater proportion of the evaporation to take place in winter but much will depend on environment. A special study of evaporation off the surface of the reservoir is clearly required.

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9. To fix normal retention level, apart from amenity considerations and the presence of roads and buildings, the level must be determined in relation to the constant tail water level at which rivers can discharge into the reservoir and the afflux levels in critical sections of the

river reaches during floods.

10. We have for the time being assumed a retention level of 16 ft. (4.88 m) above O.D. and a maximum flood rise of about 2 ft. (0.61 m). Further detailed study of the river systems may well indicate that a higher level could be maintained without significant increase in the coet of flood banks in critical reaches of the river. There would be no increase in the cost of the barrage, the height of which is determined by the level of the sea and not by the level of the water in the reservoir. Lowest draw-down level has been taken at 5 ft. (1.52 m) above O.D. and the approximate volume of water impounded between these two levels is 55,000 million gallons (249 10^6 m^3). Further study may well prove that a lower draw-down level will be practicable.

11. The shallows on the landward perimeter of the reservoir could, if left as they now exist, result in considerable plant growth which would be both unsightly and could possibly give rise to some difficulty in operation of the works. We recommend, therefore, that consideration be given to reclaiming these areas in the form of polders. The areas involved are ehown on Figure 2. The reduction in effective reservoir volume is small and has been taken account of in the figures above. It seems likely that the benefits, both from a reduction of objectionable growth and the reclaiming of land for agricultural purposee, would balance the capital cost of their construction and the annual cost of their maintenance.

12. In conclusion it will be useful to note that a minor change in the location of the barrage or in the retention and draw-down levels assumed would have a significant effect on the total storage available. The area of the water surface behind the proposed alignment of the barrage is approximately 850 million sq.ft. (78.05 km^2) and an increase in normal retention level of 1 ft. (0.305 m) would add some 10 per cent to the useful volume impounded. It may also be noted that a movement seaward of the barrage by some 1000 ft. (305 m) would increase the effective capacity of the reservoir by more than 5%. The coastlines on either side of the bay are roughly parallel so that such realignment would not add to the length of the barrage, and a survey of the bed of the bay may well show that realignment giving additional volume could be achieved without significant increase in cost.

Flood Discharge

13. For the present purpose our study of flood discharge has followed the line as proposed in "Floods in relation to Reservoir Practice" (reprint of the interim report of the Committee on Floods 1960, with additional data on floods recorded in the British Isles up to 1957).

Some 20% of the area of the catchment is subject to an average annual rainfall of about 100 inches (2564 mm). In this part of the area a run-off of 100 cusecs (2.8 m ^{3}/s) per 1000 acres (3.99 km^2) could be maintained for a number of days. For the remainder of the area we

have assumed a run-off of 50 cusecs (1.4 m^3/s) per 1000 acres (3.99 km^2) continuing for a number of days with a flood of higher intensity and short duration, 150 cusecs (4.2 m^3/s) per 1000 acres, imposed in addition. The foregoing results in a discharge of 21,000 cusecs (588 m^3/s) assumed to be maintained for several days within which period it is assumed that the discharge could increase in a period of 8 hours to 45,000 cusecs (1260 m^3/s), remain at that level for 2 hours and then fall again to 21,000 cusecs (588 m^3/s) in a further 14 hours. The above assumptions may be unduly severe. However, in view of the very large size of the reservoir in relation to the catchment as a whole the passing of a flood of this intensity and duration does not present any major difficulty nor does the cost of construction of the necessary aluice gates and spillways have a marked effect upon the cost of the barrage as a whole.

Yield

14. It has been estimated that the effective volume of water to be stored in the reservoir between +16 ft. (+4.88 m) O.D. and +5 ft. (1.525 m) O.D. is approximately 55,000 million gallons (249 10^6 m^3). It has also been estimated that the average run-off from the catchment over the three driest consecutive years (1st August 1939 to 31st July 1942) in the period 1932 to 1964 is 695 m.g.d. (36.56 m^3/s).

The cumulative discharge curve indicates that a discharge of 500 m.g.d. (26.30 m^3/s) would be realised but in the 33 years examined there were three periods when the draw-down would have been considerable; April to September 1933; February to June 1956; May to September 1959. These periods have therefore been examined more closely. The worst conditions occurred in 1933. An enlarged section of the cumulative discharge curve for that year is shown in Fig. 7 from which it will be aeen that a little more than 50,000 million gallons (226.0/10^6 m^3) would have had to be drawn from the storage by the end of September to maintain a supply of 500 m.g.d. (26.30 m^3/s). Conditions in the other two periods referred to were somewhat similar and in these periods also slightly more than 50,000 million gallons (226.0/10^6 m^3) would have been required to maintain the supply.

15. The yield described above has been compared with the corresponding figure that would be obtained from the Lapworth Curve (C.F. Lapworth, Journal Institution of Water Engineers, Vol.III, April 1949). This curve indicates a yield of about 470 m.g.d. (24.72 m^3/s), to which should be added an allowance for any excess of dry weather flow above 7% of the long term average run-off. In view of the nature of the catchment, the uncorrected yield from the Lapworth curve may well be an underestimate.

Taking all factors into account we consider that the net yield to supply, after allowing for losses, can be taken at 500 m.g.d. (26.30 m^3/s). We have not however been able to take into account the fact of possible seasonal variation in demand. We would not rule out the possibility that a full study may indicate the feasibility of a significantly higher net yield.

16. There may well be advantages in developing the Project by stages. In this event, the most suitable first stage for development would be to impound the run-off only from the Kent basin, bearing in mind the proposed location of the treatment works. This first stage would provide an effective storage volume of approximately 5,500 m.cu.ft. (154 10^6 m^3). The run-off from this basin for the three driest consecutive years is about 334 m.g.d. (17.57 m^3/s) and a net yield of up to 250 m.g.d. (13.15 m^3/s) could be obtained.

SECTION III

PROBLEMS ASSOCIATED WITH MAKING THE WATER POTABLE

The problems associated with making the water potable, the run-off from the catchment and the expected behaviour of the proposed reservoir must be examined in relation to the following factors :-

(a) physical characteristics

(b) chemical characteristics

(c) pollution

(d) biological factors

The Lancashire River Authority have made available information on the characteristics of the rivers and on drainage discharging into the river systems.

Physical Characteristics

2. The suspended solids contents of the rivers appear to be generally low. At certain times they may reach 50 to 75 parts per million (p.p.m.) or even more, but for most days in the year the suspended load appears to be much less. Storage in the reservoir will probably tend to reduce the suspended solids content of the water reaching the treatment works, particularly when it is above average in the rivers.

3. The large surface area of the reservoir will provide good conditions for oxygen exchange between the atmosphere and the water, with beneficial effect. We do not consider that stratification in the reservoir will be at all persistent, partly because of the limited depth and also because of the exposure of the large water surface to winds.

Chemical Characteristics

4. The difference in chemical constituents between the waters of the two river basins is of interest. The waters of the west basin (The Leven and the Crake) are very soft, with low alkalinity and low total dissolved solids. The total dissolved solids content is of the order of 100 p.p.m. or less, and alkalinity (as Ca CO_3) does not exceed about 25 p.p.m. The eastern basin waters (The Keer, the Kent, the Beela, the Winster and the Gilpin) are moderately hard, and their chemical characteristics appear to be quite variable. Total dissolved solids can be as high as 300 to 400 p.p.m., and alkalinity (as Ca CO_3) appears to vary at different times from some 75 p.p.m. up to as much as 200 to 250 p.p.m. It is to be noted that the waters of the Leven and Crake are likely to become fairly aggressive after taking additional

chlorides into solution and this may affect the choice of some materials to be used in construction. The variability in the proportions of the waters from the two river basins reaching the treatment works at different times is not expected to give rise to any serious difficulties.

Pollution

5. The principal drainage discharges causing pollution include seven discharging into non-tidal portions of the rivers and some thirty discharging into the river estuaries or into river channels in the bay within the area of the proposed reservoir. They are in aggregate fairly small totalling probably between 10 and 20 million gallons per day (0.53 and 1.06 m^3/s) not including etorm water. Most of this is domestic sewage with varying degrees of treatment, but it includes some 10 discharges of trade waste. The principal trade wastes are from paper mills discharging into non-tidal portions of the Beela and Kent, and from sand and gravel works, quarries, British Railways (engine sheds drainage) and chemical works diecharging into the estuaries and river channels. In the data available at present there is no evidence of the presence of toxic substances or other objectionable chemicals.

6. Chemical indicators of the state of pollution in water samples taken just above the tidal estuaries are included in the analyses at present available. They do not suggest any evidence of gross pollution in the non-tidal portions of any of the main rivers. Figures for 5-day bio-chemical oxygen demand vary from very low values up to between 1.5 and 3 p.p.m., with very few samples showing higher values, the maximum being 6.6 p.p.m. Some of the small tide-locked tributaries show evidence of much greater pollution, and it is believed that some of the sewage effluent discharges into the estuaries and river channels carry fairly beavy pollution loads.

7. It will be necessary to improve the standards of sewage treatment where required to ensure that effluent quality at least equal to the normal standard recommended by the Royal Commission on Sewage Disposal can be maintained at all times. In the case of a small number of drainage points that discharge in such a location that their effluents could be drawn into the treatment works after only a brief period of retention in the reservoir it may well be necessary to produce a epecially high standard of effluent. For such drainage points we propose that, in addition to the normal treatment, effluent polishing by rapid sand filters or other means should be adopted. Alternatively, in some instances it may be possible to divert the discharge outside the reservoir area. From the information available at present we consider that the cost of improvements to drainage works should not exceed about £1 million to £2 million.

Biological Factors

8. The main point arising under this head so far as problems in water treatment are concerned is the possibility of large quantities of algae in the reservoir. The removal of algae in water treatment is

not a new problem, and there exists considerable experience in dealing with it. The problem is however to be approached with some caution, bearing in mind the rapidity with which large masses of algae can build up in certain circumstances and the large number of different types that exist. Considerable further investigation will be necessary before proposals can be made in detail for dealing with this problem. Nevertheless, it is considered that with further study of the conditions likely to obtain it will be quite feasible to design and construct a water treatment works, generally on the lines discussed later, such that problems of operation due to the presence of algae will be reduced to a minimum.

9. There are further problems concerned with the likely establishment of rooted plants in the shallower portions of the reservoir, resulting in a tendency to clog screens during times of storm and also the possibility of causing tastes and odours. It is partly from this aspect that the proposals to construct polders have been submitted. Difficulties likely to arise from biological factors emphasise the need for efficient reservoir management.

Reduction of Initial Salinity

10. The water initially impounded during the construction of the barrage will contain a large proportion of sea water and will therefore have a very high chloride content. It will be diluted by the inflow of river water during the period when the filters and the hydraulic fill are being placed behind the permeable rock fill embankment, see Section IV. During that period the water level in the reservoir will be maintained at about 12 ft. (3.66 m) above Ordnance Datum. At a later stage of construction there will be a period of about 18 months while the barrage and motorway are being completed during which it will be permissible to raise and lower the water level in the reservoir successively without affecting construction work. During this period the reservoir will be drawn down and refilled a number of times, obtaining a dilution of about one to ten at each cycle. Assuming the run-off from the catchment at 50% above average during emptying and 25% below average during filling, and allowing also for the effect of tidal variation in limiting the discharge through the scour pipes, a cycle of emptying and refilling can be achieved within 100 days.

11. In addition to chlorides from the sea water initially impounded, there will be diffusion of chlorides from sea water held in the pores of the bed of the bay upwards into fresher water above. The rate of diffusion will depend on the difference in the concentration of chlorides in the water above and the water held in the pores of the bed, and will be reduced as the leaching process proceeds. No precise calculations can be made at this stage without knowing, for instance, the thickness of sand in the bed of the bay. However, assuming somewhat unfavourable conditions, an approximate assessment shows that it is unlikely that the chloride content of the impounded water would exceed 100 p.p.m. (as chloride) after four successive dilution cycles, as described above. On completion of the barrage, therefore, it

should be possible for the reservoir to be brought into use without any further period for desalination.

Proposals for Water Abstraction

12. A draw-off tower would be sited near the east end of the barrage with culverts leading to low level pumps and treatment works located on reclaimed land between Carnforth and Silverdale; see Figure 2. We have selected this site on the assumption that the bulk of the treated and partially treated water would be transmitted in southerly and south-easterly directions. No allowance has been included in our estimates for transmission of potable and industrial water beyond the treatment works.

The draw-off tower would be equipped with coarse and fine screens, the velocity through the latter being approximately one foot per second. We have allowed for two levels of intake gates to ensure that the water can be drawn off below the surface of the reservoir at all stages of draw-down; this also avoids having to draw from the lower levels when the reservoir is full.

The retention period in the reservoir is appreciable. For the barrage alignment proposed with a yield of 500 million gallons per day (23.30 m^3/s) retention will be 135 days with a full reservoir and 30 days with the reservoir at the lowest draw-down level.

Treatment

13. We have assumed thet the stored river water would be treated by coagulation and sedimentation followed by rapid gravity filtration and sterilization. Pre-treatment by micro-straining may be required in addition.

Such form of treatment is feasible, though may not necessarily be the most economical or the most efficient for this scheme. The detailed application of any form of treatment must await further study as, for instance, in the form of treatment outlined above, the coagulant (and possibly coagulant aid) to be used and the choice of the particular type of clarifier. The type of clarifier and its rating would be of special importance for the treatment of stored river water containing large quantities of algae at certain times. The experimental work done by the Metropolitan Water Board and described in a number of periodic reports prepared by the Director of Water Examination and published by the Board is relevant.

For the time being we have allowed for adequate capacity of clarifiers and for normal filter loading, and we have included for sterilization by super-chlorination and dechlorination as well as making allowance for pH adjustment, taste control, recovery of wash water and sludge disposal. Treated water tank capacity has been assumed at 1 to 2 hours' retention. It is of interest to note that the type of works outlined above, including preliminary treatment by micro-strainers, is being installed in Holland by the Provincial Waterwork of Nord-

Holland for treating water drawn from Ijsselmeer (21 m.g.d. - 1.10 m^3/s).

The possible use of micro strainers or rapid gravity filters followed by slow sand filters is not to be ruled out at this stage. We would expect this dual filtration form of treatment to be more expensive in initial capital cost but less expensive in the cost of operation. Over a period of say 30 years we would not expect the total expenditure to vary greatly between the two forms of treatment.

One other possibility should be mentioned; that is the use of only micro strainers with sterilization. On the information available at present it is not considered likely that this form of treatment would be satisfactory, but it should be examined because of the very large saving in cost that would result if further investigation indicated that it would be satisfactory.

Cost of Treatment Works

14. Because of the difficulty at this stage in determining the degree of treatment that will be required to provide a satisfactory potable water we have given the estimated cost in the form of limits within which we believe the actual cost, at present prices, will probably lie, and this applies both to capital and running costs. Should it be ultimately decided to adopt the dual filtration method of treatment we would expect the initial capital outlay to be higher, but the total annual charge over a long period to be little different.

We have attempted to take full account in our estimate of the more onerous conditions likely to arise.

A proportion of the water may be required for industrial purposes, which may require only partial treatment. In estimating the cost of such water we have assumed that it would be treated by coagulation and sedimentation only, and have estimated its cost accordingly. The estimated cost of untreated water is also given.

SECTION IV

THE EMBANKMENT DAM AND ASSOCIATED WORKS

Design

An outline design of the barrage is shown on Figure 5. It is essentially an embankment with a rock-filled toe on the seaward side backed by sand placed hydraulically.

The width of the embankment dam has been chosen primarily to maintain seepage losses at an acceptable amount on the assumption that it is to be constructed on sand of indeterminate depth. The width is convenient also to accommodate a dual two-lane highway.

The shape of the barrage on the seaward side and its height has been arrived at from a consideration of possible wave and tide conditions. It is fortunate that records of waves in the Irish Sea have been taken at the Morecambe Bay Light Vessel since November 1956 and as a result of a study by Mr. Draper of the National Institute of Oceanography we have accepted the significant wave height at the barrage for a 50 year period to be approximately 6 ft. (1.83 m) above extreme high water and we have made allowance for a storm surge of 5 ft. (1.53 m).

The profile of the seaward side of the embankment has been selected to reduce run-up to a minimum and subject to more detailed studies including model tests, we have taken the wave wall parapet level at+30' (9.15 m) O.D. with a roadway in rear at +25' (+7.62 m) O.D. Further protection from salt spray entering the reservoir is provided by a wall on the landward side of the embankment and by arranging that the whole of the highway surface will drain seawards.

We believe that in the long term the effects of spray over the barrage are likely to diminish. Our reason for this is based on drifter experiments carried out in the Bay by Dr. Phillips which indicate that there is likely to be an accretion of sand along the face of the barrage and a build up of a new beaching slope. This tendency could be encouraged by the construction of groins and an amount for this has been included in the estimates.

Method of Construction

2. The design of the barrage is based on the concept of forming initially a permeable rockfill bank constructed in horizontal layers across the whole length of the barrage. At the same time work would proceed on the spillway culverts and low level sluices. The rockfill would be placed on a filter layer composed of medium and coarse material. For more than 70% of the length of the barrage it will be possible to place this filter layer in the dry between tides and in this case it is envisaged that it would be protected from scour during the rising tide

by a sheet of jute, suitably pegged down, on which the first horizontal layer of rockfill would be placed during the following low tide. For that section of the embankment where the foundations lie beneath low tide level the filter layer would be placed in sandbags.

It is anticipated that the rock bank would be constructed from four points, i.e. from the neighbourhood of Hest Bank working westwards, from Cartmel peninsula working eastwards and westwards, and from Aldingham working eastwards. Once the permeable embankment had been completed to +16' (4.88 m) O.D. i.e. 1 ft. (0.305 m) above mean high water springs, sealing operations will commence by constructing a coarse and fine filter layer on the freshwater side of the bank, which will be retained in position to withstand pressure from the seaward aide by a suitable weight of hydraulically-filled sand placed simultaneously with the filter. Our proposals will make it possible to avoid the costly and difficult closure problems associated with embankment dams of this type if built initially as impervious structures.

The remainder of the hydraulic fill will follow up immediately and on its completion the reservoir level will be drawn down through low level sluices provided for the purpose to permit compaction of the fill and to ensure consolidation of the bed.

Filter material will then be built up in layers to the underside of the road, after which there will be a second draw down of reservoir level for the same purpose as before. These draw down operations will also serve to desalinate the reservoir. See Section III para. 10.

Foundation Conditions

3. In so far as the foundations of the barrage are concerned we have assumed for the present an unknown depth of sand. However indications are that over quite a large area we may expect the presence of boulder clays at comparatively shallow depths. This is confirmed by the findings of a survey carried out by Captain H. Denham, R.N., in 1845.

Before glacial times the Lake District structure had established a regular pattern of radial drainage. These main valleys were then much deepened by glacial action and in the case of Lakes Coniston and Windermere were subsequently dammed by moraines.

Boulder clay drift is extensive in the area and was followed by deposits of sand and gravels locally. The ice moved almost due south across Morecambe Bay, obliquely therefore to its geographical axis, thus giving rise to the present asymmetry of the Bay. It moved in channels at least 150 ft. (45.75 m) deep below present sea level which are now buried in drift. The present outlet from Lake Windermere, the River Leven, was a post-glacial river and the corresponding buried channels principally run due south from Cartmel and also east and west of Humphrey Head. Other buried channels may well be expected to extend below the present Leven estuary, from Winster valley, and from

the Kent gap near Grange and in the Keer channel. They could well be filled with alluvium of greater compressibility and less strength than sand. It is clear therefore that a very careful study of foundation conditions will be required before final designs are undertaken. A more detailed appreciation of the geology of the area is contained in Appendix B.

Sources of Rock

4. The economics of conetructing the barrage are closely bound up with the supply of rock for the embankment and the fine and coarse filters from suitable quarries at not too great a distance. A geological map is included as Fig. 4 and as a result of a reconnaissance of the area we show four suitable sites. Three of the sites, those located in the neighbourhood of Aldingham, Allithwaite and Jenny Brown's Point in the Silverdale area, are all composed of crystalline limestone. In all the exposures seen the epacing of the main bedding planes and of the joints were approximately equal so that supplies of cubical stone would be readily available. The fourth quarry located in Middle Scar, near Holker Park, ie of Bannisdale mud stones and slates.

Consideration has been given to the use of waste haematite ore located north of Barrow and of various slag heaps, but though the haematite ore would be suitable its distance renders it potentially uneconomic and we do not believe that any of the slag heaps would prove satiefactory.

Spillway and Sluices

5. As noted in Section II, para. 13, our assumptions are based on a 21,000 cusecs (588 m^3/s) discharge maintained for several days which could increase in a period of 8 hours to 45,000 cusecs (1260 m^3/s), remain at that level for 2 hours and then fall again to 21,000 cusecs (588 m^3/s) for a further 14 hours.

The choice of type of spillway must be considered in relation to tide levels; the worst condition being if a flood had to be discharged during Spring Tides. In calculating capacity we have assumed a high tide level of 19 ft. (5.80 m) O.D. with an addition of 3 ft. (0.915 m) to allow for surge.

Weirs, syphons or submerged orifice gates have been considered and for the time being we have selected a bottom hinged gate structure as being the most suitable. See Fig. 6. The structure will also incorporate a fish lock, the need for which is discuesed below.

We envisage that structures of this type will be required at the east and west end of the barrage. Their exact location will depend upon the results of model experiments, with the emphasis on their likely effect on navigation at Heysham and Barrow. The Figure also shows the incorporation of low level sluices. Further studies and experiments may indicate that these will have to be constructed separately in existing deep water channels. In the meantime an appropriate amount has been included in our estimate.

Fish Locks

6. We have been advised that there exist runs of both salmon and sea trout in the rivers flowing into Morecambe Bay and that if suitable arrangements are made these runs can be maintained, though it is not at present possible to ensure that they will retain the same pattern as they show at present.

We propose to provide fish passes in the barrage, together with a sufficient flow of fresh water to attract migratory fish. The type of fish pass proposed is based on the Borland fish lock which has been installed in many places in the United Kingdom and has worked satisfactorily.

Quantities

7. The principal quantities for the embankment dam are as follows :-

1.	Filter layer on bed.	Cu.yds. 800,000	(m^3	604,800)
2.	Hessian carpet.	Sq.yds. 1,000,000	(m^2	835,000)
3.	Rock fill embankment.	Cu.yds. 1,400,000	(m^3	1,058,400)
4.	Concrete Blocks for wave protection.	Cu.yds. 200,000	(m^3	166,500)
5.	Filter in rear of rock fill embankment.	Cu.yds. 500,000	(m^3	378,000)
6.	Hydraulic fill.	Cu.yds. 4,000,000	(m^3	3,024,000)
7.	Compacted fill under roadway.	Cu.yds. 3,000,000	(m^3	2,268,000)
8.	Excavation for Holker Channel.	Cu.yds. 5,000,000	(m^3	3,788,000)
9.	Flood embankment protection.	Miles 60	(km	96.60)

Construction Programme

8. If a tender is accepted towards the end of 1970 we anticipate that the contractor will require the greater part of 1971 for mobilisation and equipping himself, developing quarries and establishing stock piles so that at the beginning of 1972 construction could commence on :-

(a) Low level sluices and spillways within cofferdams.

(b) The permeable embankment dam working from four headings; from Aldingham in the west working eastwards, from the Cartmel Peninsula working east and west, and from the neighbourhood of Hest Bank working west.

We anticipate the construction of the upstream filter seal and the pumped sand fill embankment on the upstream side would be undertaken during 1973, leaving 1974 for placing the compacted fill beneath the roadway and for desalinisation operations in the reservoir. Thus completion could be expected towards the end of 1975.

Maintenance of existing Agricultural Lands

9. There are under cultivation, particularly in the Gilpin and Kent valleys, some 16,000 acres (64 km^2) of land reclaimed in the past. These landa are protected by approximately 60 miles (96.60 km) of flood banks and are drained by tidal sluices. As the reservoir will now be held at +16' (+4.88 m) O.D. it will be necessary to remove rainfall and seepage water by pumping. It will also be necessary to protect and possibly strengthen the existing embankments which will now be required to withstand a permanent head, instead of as in the past a tidal cycle witb the maximum head imposed for only a brief time in each 12 hour period. The banks will also be required to withstand wave action for prolonged periods.

New Polders

10. The use of the existing agricultural lands for what appears to be a flourishing farming industry suggests tbat new areas of ground similarly reclaimed could also be brought into cultivation. As we have already noted from the point of reservoir maintenance and operation large areas of shallow water are not desirable. Accordingly, we propose that consideration be given to the construction of poldera in the reservoir and that embankments be constructed roughly on the line of some 5 to 10 ft. (1.53 to 3.05 m) deptb of water, measured at full retention level, the land behind being drained and brought into cultivation.

The polder embankments would require a top level of +24' (+7.32 m) O.D. and they will be constructed in the main from local material with suitable protection on the reaervoir side and turfing on the landward side.

The proposed areas to be thus reclaimed are shown on Fig. 2. One large polder extends to 7000 acres (28.00 km^2) and is located in front of Arnside, Silverdale and Warton; the second large polder amounting to 5000 acres (19.97 km^2) forms an extension to the Cartmel peninsula.

Stage Development

11. We have made reference in Section II to the possibility of developing the Project in stagea should the build-up of demand necessitate sucb a course of action. The general constructional form and alignment of the barrage would be unaltered, except that in plan it would run from Hest Bank for a distance of about six miles with a return section to Humphrey Head Point to achieve a temporary end closure. For this first stage development, the two-lane carriage-way would be omitted.

The second stage of development would comprise the extension and completion of the barrage, along the original alignment, from the temporary end to the intended shore junction near Aldingham. Included in the second stage of the work would be the excavation of the connecting channel between the Leven and Kent basins, the removal of the Humphrey

Head Point return section and the construction of the two-lane carriage-way throughout the full length of the completed embankment.

SECTION V

ESTIMATES OF COST

		Low £	High £
1.	PROJECT STUDY	500,000	500,000
2.	EMBANKMENT DAM AND ASSOCIATED WORKS		
	Capital Cost		
	a) Dam, including roadway	21,000,000	26,000,000
	b) Spillways, sluices and fish lock	2,200,000	2,800,000
	c) Flood bank revetment, drainage and bridging	600,000	800,000
		23,800,000	29,600,000
	Interest during construction (7%/5 years)	4,200,000	5,200,000
		28,000,000	34,800,000
	Operation, Maintenance and Annual Charges on Capital		
	Note: Interest 7% per annum. Period of amortisation :- Heavy Civil Engineering 60 years; Buildings etc. 40 years; Electrical and Mechanical Equipment. 20 years		
	1. Operation and Maintenance	57,000	66,000
	2. Annual charges on capital	2,000,000	2,480,000
		2,057,000	2,546,000

The following table shows the equivalent cost, in pence per 1000 gallons, of the Embankment Dam, etc.

m.g.d.	100		200		300		400		500	
	Low	High	Low	High	Low	High	Low	High	Low	High
	13.5	16.7	6.8	8.4	4.5	5.6	3.4	4.2	2.7	3.3

		Low £	High £
3.	STAGE I DEVELOPMENT		
	FOR KENT ESTUARY EMBANKMENT DAM AND ASSOCIATED WORKS		
	Capital Cost		
	a) Dam, no main road	10,000,000	15,000,000
	b) Sluices and Spillway	1,000,000	1,400,000
	c) Flood bank revetment	400,000	600,000
		11,400,000	17,000,000
	Interest during construction (7%/5 years)	2,000,000	3,000,000
		13,400,000	20,000,000
	Operation, Maintenance and Annual Charges on Capital		
	1. Operation and Maintenance	30,000	40,000
	2. Annual charges on capital	955,000	1,425,000
		985,000	1,465,000

The following table shows the equivalent cost in pence per 1000 gallons (4.54 m^3), of the Kent Estuary Embankment Dam, etc.

m.g.d.	100		200		250	
	Low	High	Low	High	Low	High
	6.5	9.6	3.3	4.8	2.6	3.8

4. WATER TREATMENT WORKS

	Low £	High £
Capital Cost (for 500 m.g.d. fully treated)		
a) Intake and culverts	1,550,000	2,100,000
b) Pumping Station	850,000	1,100,000
c) Primary Treatment	10,000,000	12,500,000
d) Filtration and disinfection	11,000,000	13,800,000
	23,400,000	29,500,000
Interest during construction (7%/4 years)	3,300,000	4,100,000
	26,700,000	33,600,000
Operation, Maintenance and Annual Charges on Capital		
a) Loan charges	2,080,000	2,630,000
b) Maintenance of works	165,000	210,000
c) Electric power	135,000	175,000
d) Chemicals	610,000	790,000
e) Operation (labour)	50,000	62,000

Cost of Water in Pence per 1,000 gallons

m.g.d.	100		200		300		400		500	
	Low	High	Low	High	Low	High	Low	High	Low	High
Treated	5.1	6.6	4.4	5.6	4.2	5.3	4.1	5.2	4.0	5.1
Partially treated	3.4	4.4	2.7	3.5	2.5	3.2	2.4	3.1	2.3	3.0
Untreated	1.4	1.9	0.8	1.1	0.6	0.8	0.5	0.6	0.4	0.5

Note: Estimates of capital costs include allowances for engineering design, adminiatration, site supervision and construction model investigations.

The estimated cost of operation of the works does not include for administration.

5. STAGE I DEVELOPMENT

	Low £	High £
Capital Cost (for 250 m.g.d. fully treated)		
a) Intake and culverts	930,000	1,200,000
b) Pumping Station	470,000	600,000
c) Primary Treatment	5,000,000	6,300,000
d) Filtration and disinfection	5,500,000	6,900,000
	11,900,000	15,000,000
Interest during construction (7%/4 years)	1,400,000	1,700,000
	13,300,000	16,700,000
Operation, Maintenance and Annual Charges on Capital		
a) Loan charges	1,060,000	1,330,000
b) Maintenance of works	84,000	107,000
c) Electric power	68,000	88,000
d) Chemicals	305,000	395,000
e) Operation (labour)	37,000	47,000

Cost of Water in Pence per 1,000 gallons

m.g.d.	100		200		250	
	Low	High	Low	High	Low	High
Treated	4.6	5.9	4.2	5.3	4.1	5.2
Partially treated	2.9	3.7	2.5	3.2	2.4	3.1
Untreated	0.9	1.2	0.5	0.7	0.5	0.6

Note: Estimates of capital costs include allowances for engineering design, administration, site supervision and construction model investigations.

The estimated cost of operation of the works does not include for administration.

APPENDIX A

PROGRAMME AND ESTIMATE OF COST
FOR PROJECT STUDY

PHASE A

Work Period (15 - 18 months)

1. Work to be carried out by general contractor

Erect between 8 and 12 permanent beacons suitably located across the Bay to serve as datum points for all subsequent work by survey companies, consultants, and finally by contractors for setting-out purposes.

2. Work to be carried out under contract by survey company

(a) Volumetric analysia of reservoir capacity for various alignments of the barrage and retention levels. Photography to be carried out to a scale of 1:20,000 and 1:10,000 giving an accuracy of approximately 3%.

Ground control; to be based on Ordnance Survey trigonometrical stations in the area consisting of approximately 16 points.

Height control; will require approximately 150 milea (241.5 km) of ground level framework.

Arising from the above the volume calculations will be based on a 200 foot (61 m) grid of spot heights requiring a total of 60,000 points. Spot heights will be made on a machine equipped with apparatus to enable the co-ordinates to be punch taped for electronic computation without the need for extenaive contour mapping.

(b) A 6" to one mile map (1/10560) covering the Bay area and shoreline up to 50 feet above O.D. with contours at 5 feet (1.53 m) intervals.

(c) A hydrographic survey with echo-sounding sections to an accuracy of plus or minus one foot (0.305 m) at ½ mile (0.805 km) intervals extending to the 10 fathom (18.30 m) line or not less than 5 miles (8.05 km) from the south of the Bay. This data to be presented in a series of sections.

3. Work to be carried out under contract by soil mechanics and boring company

(a) Sub-surface investigations. - seismic and/or sonic traverses across the Bay on probable line of barrage with intensification

of investigation in such areas of difficulty as may be discovered. Borings initially at one-mile intervals, with sampling and testing of materials, with further borings as may subsequently be required.

(b) Borings and soil sampling with special reference to agricultural aspects in polder areas.

(c) Borings and assessment of possible quarry sites for construction materials and fragmentation tests.

4. Work to be undertaken by the Hydraulics Research Station

(a) Link up with hydrographic survey to ensure that idsntical reference beacons and/or Decca control will be used.

(b) Float tracking.

(i) Preliminary Study

(ii) Tracking in Detail.

(c) Current observations. Fifteen sites would be established and during the observations bed samples, suspended load samples and salinity samples would be taken.

(d) Tidal observations. Seven stations would be sstablished, of which three would be automatic and simultaneous obssrvations taken over a 28-day period.

(e) Radio-active tracer experiments.

(f) Wave observations.

5. Work to be undertaken by Consultants, with specialist advisers as necessary

(a) Draw up and let contracts for Items 1, 2 and 3 above. Supervise and co-ordinate the work.

(b) Maintain contact with Hydraulics Ressarch Station and ensure liaison.

(c) Water supply problems. Detailed studies and surveys whsre necessary of the following :-

(i) Evaporation experiments.

(ii) Study of detailed records of Newby Bridge flow charts and collaborate with Lancashire River Authority in establishing a comprehensive system of river gauging points.

(iii) Study of floods and afflux levels.

(iv) Analyses of river waters.

(v) Survey of sources of pollution.

(vi) Survey of biological factors.

(d) Land Reclamation Problems, including protection of existing areas below top water level and the development of new areas.

(e) Fishery experiments to determine direction of arrival of migratory species from the sea.

(f) Traffic study, including destination and origin surveys.

(g) Embankment dam design - experiments on flow through rockfill dam embankment and on the assessment of behaviour of tidal compartments with reference to cubature. Experiments to determine optimum shape and seaward face. Experiments to determine methods of sand consolidation.

PHASE B

Work Period (12 months)

During this period any additional boring or investigations could be carried out while work by the Hydraulics Research Station on the fixed bed model would be proceeding.

Such experiments as had not been completed during Phase A would be carried out to their conclusion, where possible. The engineers would principally be engaged in assimilating and assessing the information gained in Phase A and drafting the Feasibility Report.

PHASE C

Work Period (12 months)

Mobile bed model to be completed by Hydraulics Research Station. Final report submitted.

ESTIMATE OF COST OF FULL STUDY

		Phase A £	Phase B £
1.	Survey and soil investigations, including boring etc.	157,000	10,000
2.	Hydraulics Research Station, Survey and Model	45,000	80,000 *
3.	Consulting Engineers Costs and Specialist Fees	122,000	86,000
		324,000	176,000
	Total		500,000

* Part expenditure in Phase C

APPENDIX B

THE ENGINEERING GEOLOGY OF MORECAMBE BAY

SUMMARY

1. Throughout geological time, the Lake District massif has dominated Morecambe Bay, which only comprises its outer southern sector.

2. The much folded core of the Lake District contains Ordovician and Silurian strata, separated laterally by a central diagonal outcrop of the Borrowdale Volcanic Series; around this core, in the form of almost annular rings, lie outcrops of later Carboniferous, Permian and Triassic origin.

3. In general the dip slopes radially outwards, with an additional easterly trend superimposed in the south. Important fault zones run from the south-east to the north-west, with the downthrows consistently on the south-western sides.

4. Outcrops of Carboniferous Limestone form the greater part of the upper perimeter of Morecambe Bay, but later deposits occur at the tip of the Cartmel Peninsula. Nearer to the open sea the configuration of the coastline is much influenced by the outcrops of younger rocks. One of the Carboniferous Limestone divisions, the Urswick Limestone, is prone to solution channel formation. The catchments of the rivers entering Morecambe Bay ought to be fairly impermeable, but attention should be given to the Carboniferous outcrop in the Kent Valley up to Kendal and to some of the more permeable glacial drift.

5. Before glacial times, the domed Lake District structure had established a regular pattern of radial drainage; these main valleys were much deepened by glacial action and, in the case of Coniston and Windermere, subsequently dammed by moraines.

6. Boulder Clay drift is extensive in the area, and was followed by deposits of sands and gravels locally.

7. The ice moved almost due south across Morecambe Bay, obliquely therefore to its geographical axis, thus giving rise to the present asymmetry of the Bay. It moved in channels at least 150 feet (45.75 m) deep below present sea level, and now buried in drift.

8. The present outlet from Lake Windermere, the Leven, is a post-glacial river, and the corresponding buried channel ran due south through Cartmel towards Humphrey Head. Other buried channels must be expected to extend below the present Level estuary, from the Winster valley, from the Kent gap near

Grange and in the Keer Channel; they could well be filled with alluvium of greater compressibility and less strength than sand.

9. In some cases only the scars are offshore outcrops of solid geology, but the majority are likely to be moraine material, some of them possibly indurated by lime-bearing fresh water to form weak conglomerates.

10. The pattern of sand-protected littoral "moors" of peat and soft organic clays is well developed at points favourable to the prevailing winds around the bay. This pattern could well be "repeated" earlier at lower levels in the bay itself.

11. The unstable part of the Bay from Greenodd and from the mouth of the Gilpin River down to Lancaster Sound is the "middle section" of an estuary as defined by Wallingford. Constructing a barrage across this middle section will not only reduce the tidal cubature; it will affect the manner in which the sediment regime is maintained by vertical erosion.

12. There is some evidence that Heysham Lake is independent of the meandering Grange Channel.

13. The depth of sand in the Bay, as judged from borings plotted on Captain Denham's survey of 1843, is quite limited; except in former buried channels, it will not extend far below Chart Datum at the head of the Bay, and perhaps a further 10 to 20 feet (3.05 to 6.1 m) between Aldingham and Heysham.

14. Little evidence is available about the properties of the sands in the Bay, but inferences can be made from the observations of Captain Denham and some indirect information is available from the I.C.E. papers on the railway viaducts and approach embankments by James Brunless.

15. George Stephenson, Captain Denham and Robert Stevenson were engaged in similar investigations in Morecambe Bay when giving evidence before the Tidal Harbours Commission 120 years ago in connection with improvements in navigation in the River Lune.

1. GENERAL

Although it is a prominent geographical feature in itself, Morecambe Bay is only the outer part of a narrow sector of the isolated and dominant Lake District structure; any study of the geomorphology of the Bay therefore requires at least a cursory review of the whole area of the Cumbrian peninsula to the west of the main railway over Shap to Carlisle.

Topographically the Lake District is a circular plateau dissected by radial valleys overdeepened by glacial action, and surrounded by tracts of lower country. The principal lakes in the district are remarkable for their regular disposition radially in a concentrated group in the north, and also radially and fewer in number in the south.

The central core of the Lake District extends from Cockermouth southwards to the shores of Morecambe Bay; geologically this area broadly has three zones separated by two sharp boundaries running from WSW to ENE :-

(i) From Ennerdale, through Derwentwater to the line of the Keswick-Penrith railway.

(ii) From Broughton-in-Furness, past the heads of Coniston and Windermere and in the direction of Appleby.

The three zones thus defined are the outcrops of three geological subdivisions which, reading from north to south and in order of age, are :-

(i) North: Skiddaw Slates of Ordovician age originally shallow sea sediments of muds and sands, that have been subjected to intense pressure and folding in the Caledonian movement, to form a series of grits, flags, slates and mudstones.

(ii) Centre: Borrowdale Volcanic Series, also Ordovician in age, comprising in the main lavas, tuffs and agglomerates and containing also some intrusive rocks.

(iii) South: Silurian shales, flags and mudstones, softer than the Borrowdale rocks and giving rise to more gentle scenery in the country around Coniston and Windermere.

These ancient rocks were succeeded in the Lake District area by Carboniferous deposits and, still later, by Permian and Triassic strata, outcrops of which remain in the lower ground surrounding the central massif.

In the Furness area and in the Fylde the distribution of these later rocks is affected by faulting; the faults, extending also across the bay into the Fylde run from NNW to SSE, the down throw usually being on the

south-western side and often causing younger strata to outcrop on that side.

This remarkable distribution of a central mass of ancient rocks surrounded by annular rings of newer outcrops is due to the structural history of the area, which has undergone several submergences and upliftings, with long intervening periods of erosion. The Tertiary uplifting produced a dome-like structure of noteworthy regularity which, after erosion, left the older rocks exposed as radially dipping outcrops around the margins. On this structure was imposed the radial drainage system.

During the Glacial Period, the Early Scottish ice moved up Edenside and eastwards over the Stainmore Gap, thus having little effect on the Morecambe Bay area. However the area was much affected by the Main Glaciation when ice moved radially from the Lake District in all directions, in the north turning westwards towards Solway and the Irish Sea and in south following the existing valleys towards Morecambe Bay. The subsequent Scottish Readvance ice appears to have affected only the coastal plain of Cumberland.

The Main Glaciation thus played the dominant role in the Morecambe Bay area. It widened and deepened the existing valleys, leaving hanging tributary streams, ultimately depositing glacial drift on the lower ground and blocking valleys with moraine to form Coniston and Windermere. The general direction of movement was to the south, with a slight inclination to the east and therefore inclined to the present south-westerly trend of the lower reaches of the modern rivers. The present route of the Leven towards Greenodd from Newby Bridge is therefore a shallow post-glacial channel, the original path of the ice from Windermere directly to the south to Cartmel now being largely filled with drift.

Subsequent changes in sea level have produced a series of recent marine deposits of silty clays on the lower ground at the head of the bay. These form extensive tracts of alluvium bounded inland by the 25-foot (7.625 m) Raised Beaches, traces of which are to be found on the left bank of the Leven estuary, on the Cartmel peninsula, and on both banks of the Winster and Kent Rivers above Grange and Arnside.

The sands of Morecambe Bay are recent marine deposits with which action doubtless the formation of Mort and Morecambe Flats is associated.

In the sections that follow, further details are given of the solid geology of Morecambe Bay, starting with the last deposits of Triassic Keuper Marl at the entrance to the bay and working back to the Silurian near the head of the catchment.

2. TRIASSIC OUTCROPS

Keuper Marl lies under the blown sand on Walney Island; it occurs also under parts of the town of Barrow on the Furness mainland. More extensive outcrops lie under the drift across Morecambe Bay in the Fylde peninsula; a fault line extending S.S.E. from Preesall along the right bank of the Wyre and across the peninsula to Freckleton on the Ribble, forms the main eastern boundary, but locally there is a further rectangular outcrop of

Keuper Marl beyond this boundary in the Elswick-Inskip area. The Keuper Marl is a silty red clay with occasional bands of fine-grained sandstone, known as skerries.

Beneath the Keuper Marl lie successively the Keuper Sandstone and the Bunter Sandstone. These outcrop in the hinterland of Barrow and extend into the Bay as far as Moat Scar, near Newbiggin. On the Fleetwood shore, Keuper Sandstone has been traced on the straight coastline between Knott End and Pilling, whilst the broken coastline from Pilling, across the mouth of the Lune to the Red Nab at Heysham is the softer Bunter Sandstone. These outcrops are concealed beneath drift.

Nearer to the barrage is a further small outcrop of sandstone in the Cartmel peninsula. This lies under the lower south-western sector of the peninsula, including also the villages of Cark and Flookburgh and part of the site of the disused airfield. Presumably Cowpren Point forms part of this outcrop; sandstone fragments in a matrix of red clay occur at Lenibrick Point.

3. PERMIAN SANDSTONE

Disregarding an unimportant outcrop near Barrow, a brockram consisting of a conglomerate of Carboniferous Limestone fragments and sandstone pebbles cemented in a red sand underlies drift on Roughholme Island.

4. CARBONIFEROUS MILLSTONE GRIT

In the Cumbrian peninsula outcrops of the Coal Measures are virtually now restricted to a thin crescent extending along the coast from Whitehaven to Maryport and inland towards Carlisle; there is also a small outcrop to the East near Ingleborough. The latest Carboniferous strata to consider therefore is the Millstone Grit.

Millstone Grit outcrops over a wide rectangular area on the south-eastern side of Morecambe Bay. The major axis of this rectangle runs from the south-west to the north-east, and its corners can be conveniently defined by Heysham in the west, Kirkby Lonsdale in the north, Giggleswick in the east, and Garstang in the south. The prominent straight coastline between Heysham and Hest Bank is formed by this Millstone Grit, although the strata, admittedly, are obscured by drift. Millstone Grit also occurs to the south-west of a fault with a north-westerly trend passing through Carnforth, and its outcrop therefore is responsible for the projecting Jenny Brown's Point, to the north of the River Keer. On older maps this point was more prominent, but recent accumulations of sand in the bay below Warton Crag have tended to conceal this feature on the coastline.

There appears to be no Millstone Grit on the Furness side of the Bay, the later Permian or Triassic strata resting directly on the Carboniferous Limestone.

Records of dip are infrequent, and are doubtless influenced by the fault at Carnforth, but the general structure of the outcrop appears to be

synclinal, with the southern limb rising sharply to the heights of the Forest of Bowland. This, together with the position of the outcrop inland towards Kirkby Lonsdale, would suggest that the Millstone Grit does not extend far offshore into the Bay off Morecambe.

5. CARBONIFEROUS LIMESTONE

Carboniferous Limestone forms five important outcrops in the Morecambe Bay area :-

(i) a triangular outcrop extends from the mouth of the Duddon, inland past Barrow to Moat Scar on the Bay, and north-eastwards along the shore to Ulverston;

(ii) a much smaller, drift covered, outcrop in the low ground between the Leven and the road below Ellerside between Cark and Haverthwaite, the Ellerside escarpment being the line of a major fault;

(iii) a triangular outcrop, elso on Cartmel Peninsula, extending northwards from Allithwaite as far as a fault, collinear with that through Bolton, on the Newby Bridge - Lindale road, and excluding Newton Fell;

(iv) a major outcrop bounded by Carnforth and Arnside near to the Bay, but extending also up the Kent valley to beyond Kendal, and in the south-east defined by the Millstone Grit boundary from Hest Bank to Kirkby Lonsdale (some Carboniferous Limestone rests on the Millstone Grit on the ridge through Boulton-le-Sands);

(v) an outlier on Whitbarrow, and a smaller outlier (Low Meethop) in the Kent estuary between Grange and Arnside.

The Regional Memoir (North England) lists the Carboniferous Limestone succession for Furness and West Cumberland in descending order, but only the top two divisione are important to Morecambe Bay :-

Yoredale Group

1400 feet (427 m) of shale, sandstone and limestone zones, eandstone occurring in the second, fourth and seventh zonee from the top, and limestone sixth and ninth zones, with shales in the remaining five zones.

Urswick Limestone

375 to 400 feet (114.4 to 122.0 m) of white or cream bedded limestone particularly liable to the development of ewallow holes and solution channels as the result of weathering.

Outcrops of the Yoredale Group are to be found on the Furness coastline between Moat Scar and Aldingham and of the lower strata in Furness

northwards towards Ulverston and westwards towards Dalton. In general in this outcrop the dip is easterly at 10 degrees, increasing to about 20 degrees at Ulverston.

Carboniferous Limestone extends to Ulverston itself and also to Rame Farm between the railway, the Bay and the Ulverston Canal.

On the east side of the Leven, below the Ellerslie Scarp and concealed by drift, the Carboniferous outcrop starts again with the ten Yoredale zones outcropping over a distance of one mile in Holker Park, and lower groups emerging above the low plain at isolated points up to Haverthwaite. The dip in this outcrop is south-easterly, at 10 to 30 degrees.

The three other Carboniferous Limestone outcrops have not yet been studied in detail, in particular as regards tracing the Urswick group that might prove to be less watertight than the others, but it may be noted that Humphrey Head, where the stone is coloured brown and grey and dips to the south-east at 10 to 30 degrees, forms part of outcrop (iii) and is a much earlier deposit than those to be found near Holker Park.

6. SILURIAN

The northern boundary of the Silurian strata against the Borrowdale Volcanic Series was broadly defined in Section 1 and, at the risk of over-simplification, it must suffice to note here that the Silurian system comprises over 13,000 feet (3965 m) of folded shales and mudstones, grits and occasional sandstones that produce a topography of gently rounded hills, some 500 feet (152.5 m) high in the south and rising to more than 1500 feet (457.5 m) nearer to the centre of the Lake District dome.

Near to Morecambe Bay, the Silurian strata are represented by the Bannisdale Slates and the underlying earlier Coniston Grits and Coniston Flags.

The Bannisdale Slates comprise about 5000 feet (1525 m) of grey sandy mudstones with thin partings of sandstone, whereas the Coniston Grits and Flags consist of about the same thickness of grits and shales, the former containing significant beds of tough sandstone and the latter a greater proportion of sandy mudstones.

The Silurian outcrops approach Morecambe Bay at three points, each narrow tongue being bounded on the west side by faulting against younger strata and on the east side by unconformable horizons with later deposits. Their dips are, in general, towards the east at angles of 10 to 20 degrees; hence their tendency to run under later Carboniferous rocks towards the east, and to reappear at faults.

Thus, on the western side of the Leven and immediately to the north of Ulverston, Coniston Grits appear in the sector from north-west to N.N.E. and Bannisdale beds occur in the sector from N.N.E. to E.N.E., possibly running under the Carboniferous strata on the eastern bank.

Bannisdale beds also outcrop in the Cartmel Peninsula between the two

Carboniferous outcrops defined by the Ellerside escarpment and by the road leading from Cartmel to Newby Bridge. They reappear again east of the fault near the Lindale-Newby Bridge road and extend north-eastwards to a boundary, again with the Carboniferous, running almost due north from Milnthorpe.

Further to the north, the Silurian strata outcrop over the greater part of the catchment areas of the rivers draining into Morecambe Bay.

7. GLACIAL DRIFT

Four glacial phases are recognised in Northern England :-

(i) Scandinavian,

(ii) Early Scottish, or Western Glaciation,

(iii) Main Glaciation,

(iv) Scottish Readvance.

The Main Glaciation is the phase that has caused the glacial erosion and deposition in the Morecambe Bay area.

The height of the Lake District massif had four influences :-

(i) it advanced the onset of glacial conditions and their final disappearance;

(ii) it acted as a rampart against the advance of ice to the south, locally produced ice flowing radially outwards and turning southwards as it reached lower ground; admittedly the rampart was incomplete in the east, and some ice travelled up the Eden to cross Shap and enter the upper Lune valley, from which it approached the eastern side of Morecambe Bay past Stainton and Milnthorpe;

(iii) it caused the direction of ice movement in the Bay to be almost due south, the ice transporting with it only locally eroded materials of Ordovician and Silurian origin;

(iv) the final retreat of the ice took place from the eastern side of the country and, more slowly, from the south, ice persisting on the higher parts of the Lake District long after the main front had retreated into Scotland.

In the glacial period the present radial system of drainage was already well established and sea level in the west was depressed by at least 250 feet (76.25 m) below its present level. The ice on the fells therefore possessed sufficient potential energy to deepen the existing

V-shaped valleys into much larger troughs of conventional U-shaped glacial form, leaving the transverse tributary streams hanging above the north-south valleys. The passage of ice from the Borrowdale outcrops to the softer Silurian strata produced cwm formation by the sharp increase in erosion, and it is by no accident therefore that the heads of Coniston and Windermere lie near this boundary.

The maximum depths of both Windermere and of Coniston are about 150 feet (45.75 m), so that the lake bottom levels are now nearly at Ordnance Datum, but, as the result of siltation, this level will be much above an earlier level at the end of glaciation. A boring at Allithwaite, on the Cartmel Peninsula, showed 171 feet (52.16 m) of drift below a ground level about 25 feet (7.63 m) above Ordnance Datum. There is evidence therefore for buried glacial channels at the site of the barrage of at least 150 feet (45.75 m) below sea level, and it may be noted that present depths in the Lune Deep, off Fleetwood, reach 165 feet (50.33 m) below Ordnance Datum.

Glacial drift takes two forms. Boulder clays are deposited directly from the ice and persist in flatter sheets on higher ground, but on lower ground the deposits usually take the form of drumlins. The residual distribution is uneven both in level and thickness. Thus, there remains little boulder clay drift on the western side of the Cartmel Peninsula, whereas on the eastern side, between Kent's Bank and Cartmel, glacial drift remains up to 50 feet (15.25 m) above Ordnance Datum on Humphrey Head and up to 300 feet (91.50 m) on the nearby Fell End. Thicknesses of up to 100 feet (30.50 m) have been noted in the area, but thicknesses of 20 to 30 feet (6.10 to 9.15 m) are more common at points around the Bay. Locally the boulder clay is red, sometimes blue, and contains boulders of Lake District origin.

The second form of glacial drift is the aqueous deposits of varved clays deposited in glacial lakes and of sands and gravels dropped in the form of laminated sheets and of moraines, usually in the later receding stage of glaciation. Sheets are widespread on both flanks of the Bay, near Newbiggin for example, but moraines are more significant in the river valleys to the north. Thus at Newby Bridge, a moraine is responsible for retaining the water in Windermere and for diverting the discharge from the lake westwards. The River Leven therefore is a post-glacial river, as the former ice channel, now buried, ran southwards through Cartmel to enter the Bay between Flookburgh and Kent's Bank; hence presumably, the buried channel found in the boring at Allithwaite.

Similar buried channels must be expected in the Bay leading from the Coniston valley due south from Greenodd, in the Kent estuary due south from the Winster valley, in the same area from the gap in the Carboniferous Limestone now occupied by the Kent, and also in the Keer Channel.

The southerly trend of these glacial channels conflicts with the south-westerly aspect of Morecambe Bay, and it is possible therefore to visualise the convergence of the glacial channels at Lancaster Sound and their continuation in a south-westerly direction through the Lune Deep to the open sea. This will account for the marked asymmetry of the Bay that still persists in the modern channels.

The significance of these buried channels to the foundations of a barrage is that they will be filled with Recent post-glacial alluvium, probably with silts and clays that will be only normally consolidated; they will lack the strength and relative incompressibility of glacial drift and of strata comprising the solid geology.

8. MORECAMBE BAY SCARS

To some extent only the remarkable scar formations to be found in Morecambe Bay can be attributed to the off-shore remains of outcrops of solid geology. Thus Chapel Island in the Leven Estuary is an outlier of Carboniferous Limestone, and so is Holme Island in the Kent. Similarly some of the rocky masses off the coastline between Heysham and Hest Bank may be regarded as the remains of the outcrop of Millstone Grit.

On the other hand, other scars are not so obviously related to solid geology strata, and in these cases it is more likely that they are coarse moraine deposits, possibly eskers or marginal kames. In this category might be placed the scars at the head of the remarkable Heysham Lake which could then be regarded as the remains of one of the former glacial channels.

An explanation will be given in a later section, in connection with the work of the Tidal Harbours Commission, of the in situ "induration" of loose granular deposits. This process would tend to cement the deposits and to give them the appearance of an erratic and weak conglomerate.

9. POST-GLACIAL ALLUVIUM

Disregarding the peats and alluvium to be found locally on the higher ground of the Morecambe Bay catchments, attention is drawn to the extensive low lying marshes to be found at the head of the Bay. These follow much the same pattern as the moors of Somerset and South Wales where a coastline, formerly eroded to an elevated beachline at the 25-foot (7.63 m) contour following a temporary rise in sea level, finds new protection as sea level falls in the form of a line of dunes. The dunes consist of sand dried at low water and blown by the prevailing wind towards some obstruction near the high water line; here the dunes are either stabilised by vegetation or progressively move inland in the form of sheets of sand over low ground. The dunes themselves, often located well in front of the 25-foot (7.63 m) beach, obstruct local land drainage and cause intervening expanses of water-logged flats in which sedges and vegetation flourish and in which silt and other fine material brought down by fresh-water streams are deposited to form warps. These alluvial flats are usually established at levels near High Water Springs and, if attempts to drain them are made by means of open ditches, develop a slightly firm dessicated crust above the water table and retain below that level only the cohesive strength consistent with their own effective overburden pressure. Lacking any other means of consolidation and being markedly organic in content, at some levels containing actual bands of peat, these clays are not only weak in strength but highly compressible; typically, a thickness of some 30 feet (9.15 m) of clay and peat would consolidate about 6 inches (154 mm) under an imposed loading of only ½-ton per square foot.

Perversely the actual dunes will carry safely the loadings of traditional towns, so frequently seaside resorts develop linearly along the narrow dune line and leave between them and the hills inland a wide expanse of alluvial moors.

Walney Island and Fleetwood appear to be representative of this type of development although, admittedly, in the north of England the formation is slightly modified by the presence of glacial drift.

Nevertheless sand-protected littoral moors exist also at several points in Morecambe Bay, notably at Cockerham and Pilling Marsh, just to south of Heysham at Middleton, between Carnforth and Silverdale, and on the Cartmel Peninsula. Their absence on the western side of the Bay between Wadhead Scar and Rampside is to be expected, in view of the part played by the prevailing winds in forming the initial dunes.

Another important property of these normally consolidated clays is their sensitivity, whereby shear strengths are drastically reduced by remoulding. Changes in the salt content of the clays have a considerable bearing on sensitivity, especially when salt has been leached from the surface crust by rain.

The present alluvial moors are of relevance to the barrage scheme only from the point of view of maintaining land drainage, but they will serve also as a reminder that similar soft clays may well have been formed further offshore as the Bay was submerged in post-glacial times and are now submerged deceptively below the sands.

10. THE SAND IN THE BAY

In a paper presented to the Institution of Civil Engineers (Proceedings, March 1958, pp. 193-216), Sir Claud Inglis and J.F.T. Kestner drew attention to the tripartite form of some estuaries, notably of the River Wyre that had been closely studied by the Hydraulics Research Station. A tripartite estuary has a stable upper section, represented in the case of Morecambe Bay by the Leven above Greenodd and by the Kent above its junction with the Gilpin, and it has a stable outer estuary, in this the Lancaster Sound and Lune Deep. Between these two sections lies a middle, extremely unstable, section in which the regime is only maintained by constant changes in the position of channels.

The mechanism of regime maintenance is for sand to be moved up an estuary in suspension by wave action and the flood streams and deposited uniformly over the middle section. The balance can only be held by vertical erosion of the shoals by ebb streams concentrated in deep channels, the channels constantly moving across the width of the estuary until the distant shore is reached. When this process is reversed or recommences at the end of one of these lateral migrations, shallow littoral channels persist at each side.

This process of a migrating main channel and of smaller persistent side channels is well illustrated in Morecambe Bay, although, owing to the width of the bay, in this case there is more than one main channel.

Nevertheless this principle of horizontal accretion and of vertical erosion explains why the main channels, notably the Grange Channel, have been changing their positions continually since the time of earliest published charts.

It will be evident therefore that the construction of a barrage across the middle section of the estuary will have a profound effect upon the shoaling in the Bay. Not only will it reduce the cubature of the tidal streams; it will also put a constraint upon the continual migration of the major channels that maintain the regime.

The Hydraulics Research Station (Annual Report for 1952) studied the movement of the channels and shoals in Morecambe Bay in connection with navigation to Heysham by making comparisons between successive issues of the Admiralty Chart No. 2010 between 1845 and 1942.

Using the current issue of the chart with revisions up to 1965, it is possible to draw these broad conclusions for the seversl parts of the Bay :-

(a) Lune Deep and Lancaster Sound

Very stable over 120 years, with steep-to sides.

(b) Mort Flat and Ulverston Channel

In 1845 a much greater area was exposed at low water on Mort Flat, but this sand had been lowered by 1884 and remains substantially the same today, with exposed areas of boulders and shingle near Foulney Island.

Ulverston Channel is stable in position, but it widened and shoaled between 1845 and 1884, and remains shallow today.

(c) Furness Bank and Fisher Bank

Lower in 1884 than in 1845, and extending slightly further to the east; little change since 1884.

(d) Old Grange Channel

The major channel in 1845 and nearly straight, it became shorter, deeper and curved at its head to the east in 1884. Since then, it has shoaled considerably and its head has swung about 3 miles (4.83 km) to the west.

(e) New Grange Channel

A long channel curving round to Morecambe in 1845 (hence the Midland Railway's dock there), this channel cut into Clark Wharf by 1884 becoming etraight and deep, its head moving away from Morecambe. By 1964, it was still

straight, but shallower and it had moved bodily one mile to the north-west, but not yet to its position of 1845.

(f) Clark Wharf and Heysham Lake

The eastern side of Heysham Lake is stable, but this channel deepened between 1845 and 1884, shoaling considerably, without loss in length, since then.

Clark Wharf, in 1845 an extensive shoal drying at low water, was narrowed by 1884 and split into two shoals with a new shallow channel between them by 1964. This forcing of Clark Wharf in an easterly direction caused a narrowing of Heysham Lake, but it is possible that this section has now reached a limit.

The conclusions reached by Wallingford and given in the Annual Report were based on a survey made in 1942, the chart having only unspecified minor corrections made to it subsequently. However H.M. Surveying Ship "Medusa" made a new survey near Heysham from April to June 1964. This survey, which has not yet been published, confirmed the stability of the inshore channel between the mainland and Clark Wharf, and it has indicated also a narrowing of the channel between Clark Wharf and Clark Wharf Spit, largely on the western side, and, on a large scale, a movement of the Grange Channel to the north-west by over 2,000 feet (610 m).

As a result, Clark Wharf Spit has increased considerably in size and the area uncovered at chart datum is continuous with Old Scar Bank, off Morecambe.

It is premature at this stage to draw further conclusions from the new survey, but the independence of Heysham Lake from the oscillations of Grange Channel deserves further consideration.

Some indications of the depths of the sand in Morecambe Bay can be obtained from the logs of borings plotted on Captain H.M. Denham's survey of 1843. There is no record on the survey as to when these borings were undertaken; none are much deeper than 20 feet (6.1 m) and the descriptions of the strata encountered naturally lack the precision of modern site investigations. Nevertheless the borings show clearly that at the head of the bay the thickness of the sand is quite limited.

It is dangerous to draw conclusions from borings, however numerous, scattered over a wide area, since there are no grounds for supposing that the base of the aand is regular; moreover changes in level at buried channels are probably more abrupt than over greater distances. Nevertheless, with these provisos it is possible to make these broad deductions of base levels of the sand below modern Ordnance Datum :-

Leven Estuary		Kent Estuary	
Greenodd	4 feet (1.22 m)	Grange	3 feet (0.915 m)
Leven Viaduct	6 feet (1.83 m)	Kent's Bank	15 feet (4.575 m)
Entrance to Canal	8 feet (2.44 m)	3½ miles (5.64 km) W.N.W. of Bolton Church	20 feet (6.10 m)
Aldingham	21 feet (6.41 m)	1½ miles (2.42 km) N.W. of Poulton Church	15 feet (4.575 m)
3¼ miles (5.23 km) S.E. of Aldingham	32 feet (9.76 m)		

In each case the borings were sunk off the points named, well offshore but to the side of the channels as then existing.

Several borings were sunk up to 4¼ miles (6.84 km) off the Cartmel Peninsula without reaching the base of the sand, except in one instance where Denham recorded clay at a level of 10 feet (3.05 m) below Ordnance Datum.

On his survey, Denham frequently described the sand as being continuously compact (throughout its thickness) and as being hard on the surface; these descriptions are consistent with the movement over it of wheeled vehicles at low tide. At the other end of the scale, he occasionally recorded isolate spurs of sand as "quick", but in each case these occur at points where steep hydraulic gradients are to be expected.

The strengths of strata below the sand are not described.

11. ENGINEERING WORKS IN MORECAMBE BAY

(a) Heysham Oil Jetty

(Institution of Civil Engineers, Maritime & Waterways Division Paper No. 9, 1947-8)

In this paper by Professor A.L.L. Baker, attention was drawn particularly to the design of the bell-type dolphins; these dolphins are carried on Larrsen box piles driven into boulder clay. Preliminary test piles, 18 inches (461.52 mm) square, driven 15 to 20 feet (4.57 to 6.10 m) into this clay were expected to have an ultimate resistance of 150-200 tons, and to have an immediate resistance to withdrawal of 15-20 tons.

Silt is mentioned on the sea bed, but it is entirely consistent with the findings from Denham's survey that there is no mention of sand on the site of the jetty in a depth of about 5 fathoms (9.15 m).

(b) The Leven and Kent Viaducts

(Proceedings of the Institution of Civil Engineers, Vol.17, 1857-8, pp. 442-8)

In his paper, James Brunless described the strata at the site of the Leven and Kent viaducts as consisting respectively of 9 and 7 feet (2.75

and 2.14 m) of calcareous rock detritus, broken shells and living molluscs resting on 50 to 70 feet (15.25 to 21.35 m) of shelly material having the appearance of marl. Exposed, the material consisted of the "finest comminuted dust" which, when dried, was readily driven away by the wind and which, when wet, formed quicksands. The description fits that of a fine calcareous silty sand.

Unless the stated depth is taken to refer to that at the centre of the channel (where Denham reported only "concrete of sand" to a depth of 12 feet (3.66 m) below Ordnance Datum), there is a significant discrepancy between the two records. The piles adopted for both viaducts were 10 inches (256.4 mm) in external diameter and $\frac{3}{4}$-inch (19.23 mm) in wall thickness, fitted with 30-inch (769.2 mm) diameter discs at the base. Tests on piles sunk by kentledge and vibration showed that their ultimate bearing load was equal to 5 tons per square foot (0.55 kg/mm^2), when sunk to depths of 16 to 23 feet (4.88 to 7.02 m).

For the viaducts as constructed, similar piles were sunk by jetting to depths of 20 feet (6.10 m), and loaded to 20 tons. At the telescopic navigation span in each bridge, the piles were sunk to 26 feet (7.93 m).

Rail level on the Leven Viaduct was 28 feet (7.93 m) above low water; on the Kent Viaduct it was 23 feet (7.02 m).

Both viaducts, having timber decks, were completed in 1857, and were reconstructed in 1885 and 1886, and in 1914; the extent of reconstruction has not been ascertained.

Brunless presented an earlier paper to the Institution in 1885 (Proceedings, Vol.14, pp. 239-250) in which he described the construction of the approach embankments. The sands in the estuary stood well in water at a slope of $1\frac{1}{2}$ to 1. In the most exposed parts, rail level was 15'-6" (4.73 m) above the high water of ordinary spring tides (6'-3" and 4'-3" (1.91 and 1.30 m) above the extraordinary tide (tides) of the 27th December 1852); the seaward pitched batter had a slope of 2 to 1, and carried a low wave wall rising 30 inches (769.2 mm) above rail level.

(c) Heysham Harbour

(Proceedings of the Institution of Civil Engineere, Vol.166, 1905-6, pp. 229-242)

In this paper by G.N. Abernethy, a description is given of the construction of this harbour for the Midland Railway Company. Work started in 1897 with the tipping of twin sandstone and clay breakwaters on the sandy foreshore, final temporary closure being achieved by tipping from a timber viaduct. Sandstone was encountered in excavations over the greater part of the dock area.

12. THE TIDAL HARBOURSCOMMISSION

The first report of the Commissioners "appointed to inquire into the State of Tidal Harbours" was published in 1845; a second report appeared

in 1846. The Commissioners were charged with investigating changes that had occurred in tidal harbours, measures to alleviate problems of navigation at various ports, the powers necessary for conservation, and measures to adopt for the general improvements to harbours and navigable rivers.

The River Lune, serving the Port of Lancaster, was amongst the harbours examined; Lancaster at that time was developing as a major railway centre, but access to its wharves was deteriorating, trade being affected also by new port developments at Fleetwood.

Evidence was given advocating improvements in the river above Sunderland Point, but Captain H.M. Denham, R.N., F.R.S., the hydrographer responsible for the 1844 survey of Morecambe Bay, held that the fundamental, and insuperable, problem was the sand bar, four miles in length, across the Shoulder of the Lune into Heysham Lake, since the set of the tidal streams was across the meagre channel. Denham advocated the construction of a new port at Poulton Ring (Morecambe), where up to 30 feet (9.15 m) of water was to be found at low water at the head of the New Grange Channel and in the lee of Clark Wharf Shoal. Unobstructed depths of 15 to 20 feet (4.58 to 6.10 m) of water in the approach channel would be available if a "muscle scare" obstruction at Low Scare was removed. Denham's proposal, which was supported by Robert Stevenson & Sons, envisaged the construction of a pier, three-quarters of a mile (1.21 km) in length, at the boulder covered scar of marl known as Old Scare. Stevenson's plans included also in the works, estimated at £220,000, a 6½ acre (0.026 km^2) dock. The Grange Channel, according to a survey made by Murdoch Mackenzie for the Admiralty in 1770, had been stable for 70 years, and Denham was forced to regard as unacceptable another survey, made in 1826, that indicated that immense differences had occurred in the previous nineteen years.

On the current chart, the Grange Channel still exists in a curtailed form, but the 1884 chart shows that the channels had moved away from Morecambe to such an extent that the Railway Company was obliged to abandon its packet port there and to construct a new dock at Heysham, opened in 1904.

At the time of the Commission, George Stephenson as Engineer to the Whitehaven and Furness Junction Railroad, was considering plans for building a railway embankment across the Duddon estuary, the idea being to dump boulders from chain-drawn waggons carried on a piled timber staging. The boulders were to be tipped in uniform lifts across the estuary, and no attempt was to be made to stop the tidal streams until the last stages of construction were reached. After the Duddon embankment had been completed (construction actually was never started), the Company intended to revive plans for a similar embankment across Morecambe Bay. Thus Stephenson and Denham were brought into conflict, the latter stating in evidence connection with his proposals for Poulton Harbour: "Hesitation or supineness may bring about a project for enclosing the bay; and though such would not be permitted of the harbour enterprize, yet the first in the field is always forearmed and can dispute reasonably the ground".

Stephenson evidently intended to adopt similar construction methods

for his Morecambe Bay proposals in 1836, for in his evidence before the Commission he spoke of his resignation as Engineer to the Junction Railway when the Directors of the Company deleted from the report as published his opinion that an embankment would be too costly for the shareholders and that it would require government support. Stephenson was replaced by a Mr. Hague, whose plans for a timber railway bridge beside which sand would be allowed slowly to collect by tidal action, thus permitting in course of time valuable land reclamation, were regarded by Stephenson as impracticable. Financial support for Hague's proposal was lacking however in 1838, and a railway link to Lancaster further inland by means of the viaducts across the Leven and Kent Rivers, was not completed until 1857.

Hague's report to the Caledonian, West Cumberland and Furness Railway Company was published in the Civil Engineer and Architect's Journal of 1838, pp. 409-411. The line of the embankment was to have been from Poulton Ring WNE to a point near Newbiggin. Timber piles and a cut-off were to have been driven through the sands to the underlying clay, and a rubble core was to have been tipped, against which it was hoped to form naturally a beach. Hague prepared a section of the bay giving levels to the clay stratum, but it was not reproduced in the Journal. Nevertheless the levels were plotted as Section A-D on the survey by Captain Denham.

Several references were made in the evidence put before the Commission to "scares", "skaers", or "scars". Captain Denham has also used the phrases "indurated sand" and "concrete of sand and silt" in connection with his survey of Morecambe Bay. The question arises as to whether these scars are merely recent shoals of gravel, whether they are outcrops of solid geological formations, or whether they are remains of glacial moraines, to a considerable extent bound together in a calcareous matrix at points where acidic ground waters having passed underground through limestone strata force their way upwards to the sea bed through the permeable moraine material and, meeting water of higher pH-value, precipitate calcium carbonate. This action is the basis of modern research into the formation of Beach Rock, but it is quite evident that it was fully understood by Captain John Fisher, R.N., Harbour Master of the Port of London when, in giving evidence to the Tidal Harbours Commission in 1845; he said about the Whiting Shoal in Limehouse Reach: "There is a sample of it here; it resembles plum-pudding stone, or a conglomerate of gravel, oyster and other shells; apparently being a calcareous cement. This has been in a loose state; it is probably the action of a mineral spring, which has come up through the water, that hardens it".

Equally impressive is Robert Stephenson's report of 1837 on improvements to the Ribble, reprinted by the Commission in their Second Report, for its full understanding of cubature in maintaining estuary channels and of density currents.

SEA-BED DRIFTER EXPERIMENTS IN MORECAMBE BAY

Three hundred drifters, in equal batches of 50, were released at six points in the outer parts of Morecambe Bay on the 7th December, 1965; the release formed part of a programme of research into sediment transport by Dr. Ada W. Phillips of the Department of Geography, University of Lancaster.

Each drifter comprised a 7-inch (179.48 mm) diameter plastic cup attached to a weighted polyvinyl rod, 21 inches (538.44 mm) long, and bearing a postage-paid card for identification on recovery.

Four of the release points were on a line between the entrance channel to Barrow and the mouth of the Lune and also in line respectively with the Ulverston Channel, Lancaster Sound, Grange Channel and Heysham Lake. The other two release points were near the Lightning Knoll Buoy and at the entrance to the Lune Deep.

It is sometimes held that neutrally buoyant sea-bed drifters provide no reliable guide to sediment transport, since a proportion of them will be thrown up on shorelines irrespective of a dominant movement of the sand. Furthermore, water movements near the sea-bed, being controlled both by tidal streams and by the effects of wind, may not influence the drifters and the sand in the same way. Nevertheless, the low cost of drifters and their high mobility provide an inexpensive and accelerated means of determining at least broad trends of sediment transport. Objections to their use for this limited purpose may be less when, as in this case, some dominant directions of movement are discernible.

A summary of the recovery of the drifters over a period of 4¾ months is given on the attached table. During this period records of the wind velocities at Barrow and of the wave periods at the southern end of Walney Island were obtained.

Of the 73 drifters recovered (24.3%), nearly half were found on Walney Island and in the entrance to Barrow near Piel Island. They originated from all the release points, but with fewer contributions from Heysham Lake and the Lune Deep. Although it is possible that they migrated by a straight route to the W.N.W., it seems more likely that they were carried out to sea and returned to the coastline further to the north, many of them finding their way round the recurved southern end of Walney Island.

More than one quarter of the drifters were recovered from the north-western shore of the Bay, mainly between the Point of Comfort and Baycliff. They could have taken direct northerly routes to their destinations; however, as the greater number were recovered later than those on Walney, it is also possible that they travelled via the open sea, particularly in the case of those released near the Fylde coastline.

Of the remaining quarter of the drifters, a few reached the beaches at Morecambe and on the Fylde but the greater number were recovered quickly by fishermen working in the middle of the Bay.

The important conclusions to be drawn from this investigation, therefore, are the great preponderance of drifters that reached the north-west coastline and the virtual absence of them on the northern and eastern shores. Although the sand in the Bay may be in regime and constant in volume, as the Hydraulics Research Station found some years ago, there are indications of a marked clockwise circulation of sand around the Bay, material being brought in from the direction of the Lightning Knoll Buoy and discharged through the Lune Deep.

This rotation would be entirely consistent with the asymmetry of the Bay, the pressure of Clark Wharf on the inshore channel to Heysham, the progressive accretion to be observed at Jenny Brown's Point near Silverdale and, possibly, with a number of west to east channels to be seen crossing the sands off Humphrey Head.

Further investigations would be necessary to support this tentative deduction, particularly by observing tidal streams within the Bay. However, if it proved that the sand regime was indeed maintained by the ebb streams from the eastern side of the Bay, it would appear that the reduction of tidal cubature would reduce the depth of the navigation channele by accretion.

MORECAMBE BAY - SEA-BED DRIFTER RESEARCH

(SOURCE: REPORT BY DR. A. W. PHILLIPS, UNIVERSITY OF LANCASTER - 26.4.66.)

(6 x 50 DRIFTERS RELEASED 7.12.65.)

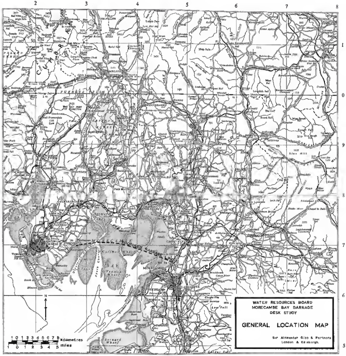
RELEASE POINT / RECOVERY POINT	LIGHTNING KNOLL	ULVERSTON CHANNEL	LANCASTER SOUND	GRANGE CHANNEL	HEYSHAM LAKE	LUNE DEEP	ALL RELEASE POINTS
WALNEY IS./PIEL ISLAND	* 0-1-0-3-0 =4	1-1-2-2-1 =7	1-2-0-1-4 =8	4-0-0-4-2 =10	0-0-0-1-1 =2	0-2-0-1-1 =4	6-6-2-12-9 = 35
ALDINGHAM	0-1-0-2-1 =4	1-1-0-5-0 =7	0-0-1-3-0 =4	0-0-0-0-0 =0	0-0-0-2-0 =2	0-0-1-1-0 =2	1-2-2-13-1 = 19
CARTMEL PENIN.	0-0-0-0-0 =0	0-0-0-0-0 =0	0-0-0-0-0 =0	0-0-0-0-0 =0	0-0-0-0-1 =1	0-0-0-0-0 =0	0-0-0-0-1 = 1
MORECAMBE	0-0-0-0-0 =0	1-0-0-0-0 =1	0-0-0-0-0 =0	0-0-0-0-0 =0	1-2-0-0-0 =3	0-0-0-0-0 =0	2-2-0-0-0 = 4
FYLDE	1-0-0-0-0 =1	0-0-0-0-1 =1	0-0-0-0-0 =0	0-0-0-0-0 =0	0-1-0-0-0 =1	0-0-0-0-0 =0	1-1-0-0-1 = 3
IN THE BAY	0-0-0-0-0 =0	0-0-0-0-0 =0	0-0-0-0-0 =0	1-0-0-0-0 =1	7-0-0-0-0 =7	1-0-1-1-0 =3	9-0-1-1-0- = 11
ALL RECOVERY POINTS	1-2-0-5-1 =9	3-2-2-7-2 =16	1-2-1-4-4 =12	5-0-0-4-2 =11	8-3-0-3-2 =16	1-2-2-3-1 =9	19-11-5-26-12 = 73
(PERCENTAGE RECOVERY)	(18)	(32)	(24)	(22)	(32)	(18)	(24.3)

* This indicates the following recoveries :-

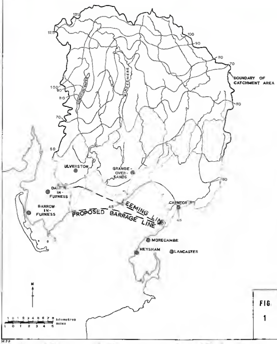
Month 1 - 7.12.65 - 6.1.66 - Nil
Month 2 - 7. 1.66 - 6.2.66 - 1
Month 3 - 7. 2.66 - 6.3.66 - Nil
Month 4 - 7. 3.66 - 6.4.66 - 3
Month 5 - 7. 4.66 -26.4.66 - Nil

Total - 4

D 61494/1/Dd129201 K12 9/66 CL


WATER RESOURCES BOARD
MORECAMBE BAY BARRAGE
DESK STUDY
GENERAL LOCATION MAP
Sir Alexander Gibb & Partners
London & Edinburgh.
kilometres
miles
MORECAMBE
LANCASTER
BARROW
ULVERSTON
CARNFORTH
KENDAL
WINDERMERE
MORECAMBE BAY BARRAGE LINE

M F P



EQUIVALENT VALUES OF ISOHYETS IN INCHES & MILLIMETRES	
inches	millimetres
45	1143 0
50	1270 0
60	1524 0
70	1778 0
80	2032 0
90	2286 0
100	2540 0
125	3175 0

FIG. 1

WATER RESOURCES BOARD
MORECAMBE BAY BARRAGE
DESK STUDY

MAP OF CATCHMENT AREA SHOWING ISOHYETALS

Sir Alexander Gibb & Partners, London & Edinburgh

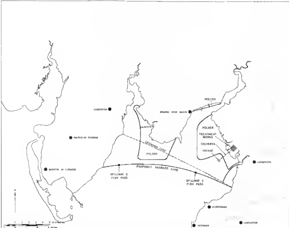


FIG 2

WATER RESOURCES BOARD
MORECAMBE BAY BARRAGE
DESK STUDY

KEY PLAN
BARRAGE AND POLDERS

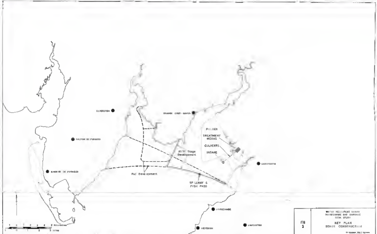


FIG 3

WATER RESOURCES BOARD
MORECAMBE BAY BARRAGE
DESK STUDY

KEY PLAN
STAGE CONSTRUCTION

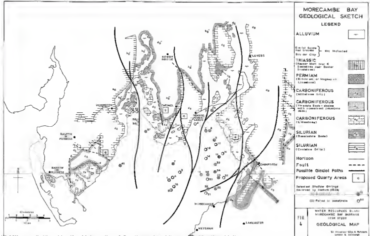


FIG. 4
GEOLOGICAL MAP

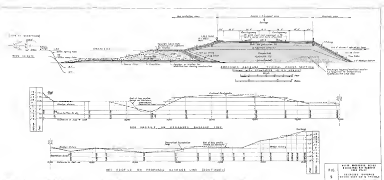
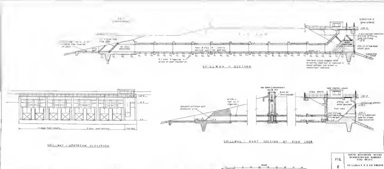


FIG. 5

PROPOSED BARRAGE


SPILLWAY - SECTION
SPILLWAY - UPSTREAM ELEVATION
SPILLWAY. PART SECTION AT FISH LOCK
FIG.
6

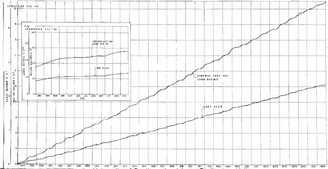


FIG 7